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# Self-contained Diving Operations in McMurdo Sound, Antarctica: Observations of the Sub-ice Environment of the Weddell Seal, *Leptonychotes weddelli* (Lesson)

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(Plates I-III; Text-figures 1-5)

### INTRODUCTION

DIVING with self-contained underwater breathing apparatus (SCUBA) has proved to be a valuable scientific tool, permitting the investigator to probe personally into the underwater environment. Its principal use has been in temperate to tropical littoral waters. As scientists gain experience in diving technology, its use is spreading farther afield.

During October and November, 1963, the New York Zoological Society sponsored an expedition to McMurdo Sound, Antarctica, for a study of the physiology and ecology of the Weddell seal, *Leptonychotes weddelli* (Lesson). At that location at that time of year, the Sound is covered with an almost solid layer of 2-4 m. ice. A significant part of our investigation involved submarine observation with SCUBA under the sea ice to know firsthand the conditions in which the seal exists and to record the sound emissions which seals may use for navigation and/or communication. Sound production by phocid seals has been the subject of a preliminary study by Schevill, Watkins & Ray (1963) and Weddell seal sound production and its possible significance have been described by Ray & Lavallee (in manuscript) and Schevill & Watkins (in manuscript).

Techniques of polar diving are very different from those used in warmer waters, and much of the known information has not been published. Fane (1959), Neushul (1961) and the U. S. Navy Diving Manual (1963) discuss some techniques of cold-water or polar diving, but none treats the special problem of diving under solid sea ice. Articles in diving magazines have dealt with the similar, but not so rigorous, subject of sub-ice lake diving. Therefore little is known about the reliability of open-circuit breathing apparatus or of the physiological effects on divers under field conditions under sea ice in locations such as Antarctica.

The diving program was divided into two phases, based on the advice and publications available. The first was to test materiel and observe physiological phenomena on divers using open-circuit lungs in a preliminary effort to establish possible endurance limits. The second phase was to make observations and photograph the sub-ice environment. Testing was carried out to determine: (1) performance of valve blocks and regulators; (2) exposure protection and buoyancy problems of the diving suit; (3) physiological problems such as vertigo, loss of orientation, nitrogen narcosis threshold, low temperature torpidity and cramps; (4) reliability of photographic equipment, battery lamps, depth gauges and surface-supplied floodlights.

### ACKNOWLEDGMENTS

This program was supported by Grant GA-57, Office of Antarctic Programs, National Science Foundation, to the New York Zoological Society, and by the Commander, U. S. Naval Antarctic Support Force. Some physiological equipment was supplied through Grant AINA 76 from the Arctic Institute of North America to the New York Zoological Society.

Considerable help prior to our expedition was received from personal communication with Dr. M. Neushul of the University of California at Santa Barbara and from Mr. Verne Peckham of Stanford University. Additional aid and ad-

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vice were given by Lt. Commander Glenn Brewer, U.S.N., of the submarine *USS James Monroe,* who dived in the Arctic Ocean under the ice. The sound and consistent advice of these men was extremely helpful in the selection of equipment and in planning and carrying out the dives.

Our field operations would have been impossible without the logistic support of the USARP office and personnel based at McMurdo and the help of Dr. Donald Wohlschlag and his assistants of the McMurdo Biological Laboratory. Mr. Elmer T. Feltz of the Arctic Health Research Center, Anchorage (a member of the expedition team), and Mr. Gerald Kooyman of the University of Arizona gave unstinted aid in field operations as did Lewis E. Roane, PH2, Billy D. Douthit, PH3, and Joseph B. Phillips, AN, of the Atlantic Fleet Mobile Photo Unit, U.S.N., Norfolk.

The following read and criticized this paper: Dr. Donald Wohlschlag, Dr. Michael Neushul, Mr. Verne Peckham, Dr. John Bunt of Sydney University and Dr. Laurence Irving of the University of Alaska.

## MATERIEL

The following equipment was taken for the diving operations:

Neoprene exposure suit (wet type). See below for details.

Two sets of compressed air lungs. Twin 70 cubic foot (4000 L) steel bottles with "J" reserve air block, 2150 psi.

Two double-hose, 2-stage regulators (Aqua Master, U. S. Divers).

One single-hose, 2-stage regulator with pressure gauge (Sportsways Waterlung).

Weight belts, masks, flippers, depth gauges, diving watches, underwater knives, underwater flashlights.

Inflatable diving safety vests.

Underwater battery-powered sealed-beam lights.

Two 1,000-watt floodlights and cable, with spare bulbs.

One Xenon flashing beacon in watertight case.

Four 15-pound grapnels.

Four cork buoys.

Four small styrofoam buoys.

600 feet of ⅜-inch braided nylon line.

1,000 feet of nylon parachute cord.

One Navy-type diving stage (one man).

The selection of exposure suits was of particular concern. Mobility and a certain amount of comfort were desired. A combination of a wet suit with a dry suit worn over it would offer the greatest endurance, although bulky. Information on chemical, or electrically heated, suits was not available, if such devices are in existence. A ¼-inch (6 mm.) neoprene wet suit was chosen as the most practical in shallow water. Commander Brewer, Dr. Neushul and Mr. Peckham recommended this thickness from their experiences.

Parkways Fabricators of South Amboy, New Jersey, assisted in designing and tailoring a satisfactory suit. With some minor modifications this suit would be ideal for shallow water diving. The suit consisted of three major pieces. The ¼-inch (6 mm.) pants came up to the armpits in a modified "farmer Brown" design. A ⅛-inch (3 mm.) thick armless undershirt with attached hood was worn under a ¼-inch jumper with a separate hood. Zippers were eliminated to minimize water entry. The three-fingered gloves and the boots were made large enough to prevent restrictions of blood circulation. To increase the thermal insulation, a very low density neoprene was used; all components were lined with stretch nylon. The outer hood was designed to come low over the forehead to protect the sinuses. The bottom part had a chin cup, so that with the mask in place only a minimum of flesh was exposed to the water.

Other equipment and support to carry out the diving was supplied as an integral part of Base operations and consisted of:

Electrically driven, 3-stage Cyclone air compressor.

An insulated hut, 2.4 × 3.6 m. with a 1.3 $m^2$. hole in the floor.

Oil heater.

2.5 kw. gasoline generator.

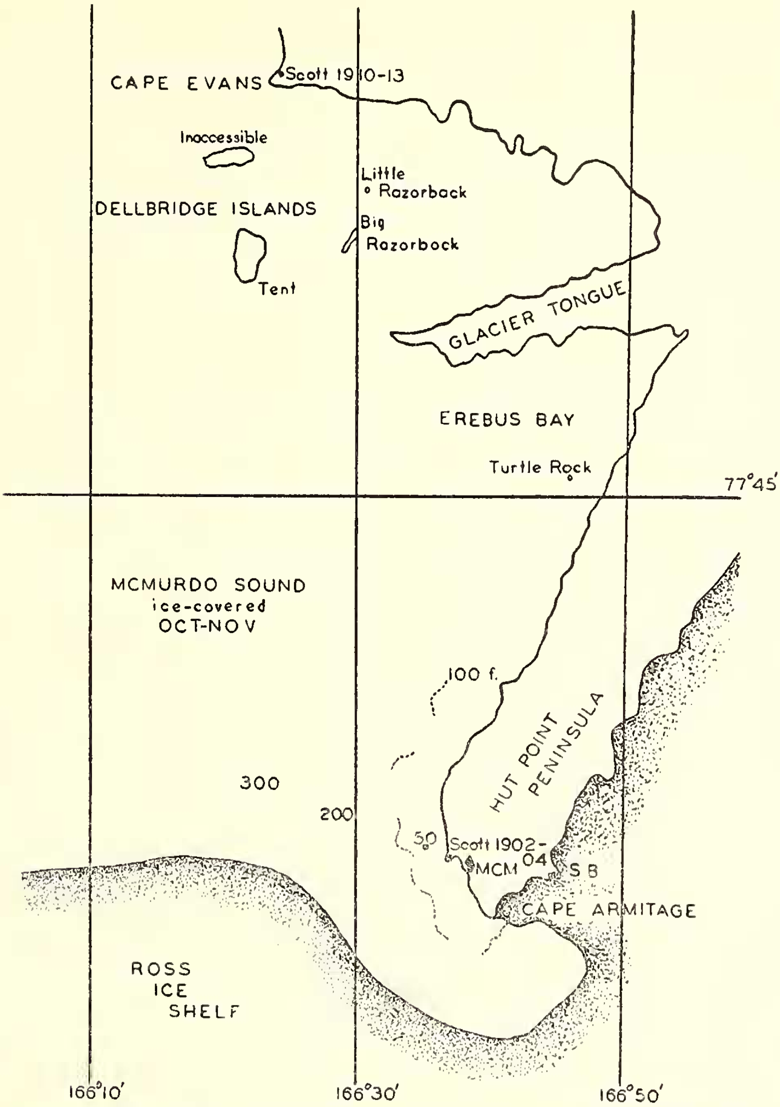
Diving ladder and strongbacks (for suspending the descending line and diving stage below the hole).

Coleman lantern, jerry cans, fuel, shovels, dipnets, ice chisels, chain saw, ice tongs.

Compressed air for the lungs was supplied by the air compressor installed in the Biology Laboratory. The intake for the compressor was extended to the outside atmosphere. This dry, cold air supply reduced the possibility of water accumulation through condensation and the resultant freezing at the regulator high-pressure stage during diving operations.

## OPERATIONS

*Preparatory.*—A point was selected on the sea ice in McMurdo Sound, about a quarter of a mile offshore (Text-fig. 1). The weather was still quite cold, early Spring temperatures running —20 to



Text-fig. 1. McMurdo Sound from Cape Evans to Cape Armitage. MCM = McMurdo Station (USA). SB = Scott Base (NZ). Soundings are in fathoms: 50 = location of diving hut. Redrawn from chart HO 6666.

–30°C with winds gusting to 40 knots or more on some days (Table 1). Water temperature under the ice was –1.9°C. Ice thickness varied from 2 to 3.5 m.

Text-fig. 2 and Plates I-III show our diving operation. A shelter was necessary from which diving operations could be conducted. This permitted divers to enter and leave the water in a warm atmosphere. First, a hole had to be cut through the hard sea ice. A 2 $m^2$. area was marked off and swept clear of snow. The ice was sliced into squares with a chain saw and then broken into blocks by stabbing between the cuts with a long-handled chisel. These cubes, weighing approximately 30 kg., were then lifted out with tongs. The process was repeated until a bottom layer of about 15 cm. remained. The ice removed from the hole had to be dragged some distance to distribute the weight. Past experience of scientists cutting holes in the thick sea ice had shown that ice removed from the hole and concentrated in an adjacent area caused drifting of snow. The combined weight of the blocks and snow pressed the ice down and water flooded over the edges of the hole. Usually, an ice sounding is taken by drilling a 1½-inch (4 cm.) hole in an adjacent area. When this was attempted, the bit became frozen in the ice and

Table 1. Résumé of Dives Made, With Ambient Weather Conditions Observed Partly by the Authors and Partly by the U. S. Navy at McMurdo Station.

| No. | Date 1963 | Time | Duration (minutes) | Air T° C | Hut T° C | Water T° C | Wind (knots) | Total Skycover % | Purpose | Depth (meters) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 31 Oct. | 1700-1720 | 20 | −20 |  | −1.9 | 20 E | 60 | Initial test | 5 |
| 2 | 1 Nov. | late afternoon | 20 | −18 | −2 | −1.9 | 25-30 NE | 30 | Initial test | 5 |
| 3 | 5 Nov. | 1631-1656 | 25 | −12 | 11 | −1.9 | 5-10 E | 50 | Physiological | 1 |
| 4 | 6 Nov. | 1520-1550 | 30 | −6 | 15 est. | −1.9 | 0 | 0 | Testing gear | 10 |
| 5 | 7 Nov. | 1500-1520 | 20 | −4 | 15 est. | −1.9 | 0 | 60 | Observation of ice and seals | 25 |
| 6 | 8 Nov. | 1745-1810 | 25 | −8 |  | −1.9 | 14 E |  | Observation of ice | 25 |
| 7 | 9 Nov. | 1452-1526 | 34 | −7 | 15 est. | −1.9 | 15 NW | 30 | Physiological | 1 |
| 8 | 10 Nov. | 2130-2200 | 30 | −6 |  | −1.9 | 14 SE | 10 | Observation of ice | 10 |
| 9 | 11 Nov. | 2330-2401 | 31 | −4 | 15 est. | −1.9 | 8 NE | 80 | Physiological | 1 |
| 10 | 12 Nov. | 2000-2030 | 30 | −4 |  | −1.9 | 8 SE | 60 | Observation of ice and seals | 12 |

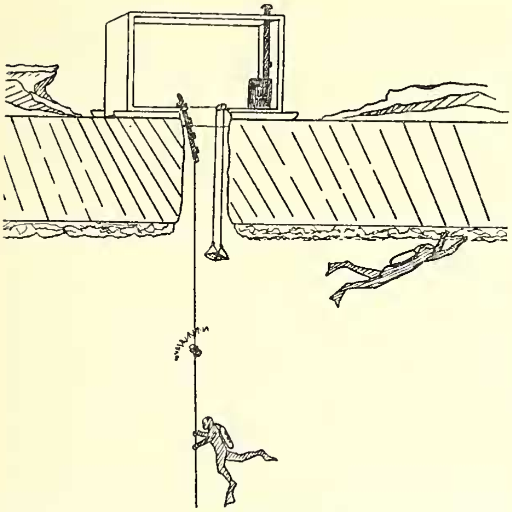
the operation was abandoned. Our not knowing the exact thickness of the ice slowed the cutting process considerably, and it was necessary to proceed with caution near the bottom. Once a hole was made through the final layer, water flooded over the edges of the hole. Usually 25 cm. of the top. After the hole had flooded, the final layer was chopped out with a long-handled chisel. The time required to clear the 2.3 m. hole was 32 man-hours of heavy labor. Techniques involving blasting considerably lighten this work load, but these were not used by us.

When the hole had been completed, a prefabricated heated hut, 2.4 × 3.6 m., was dragged into place. The hut had a 1.3 $m^2$. opening in the floor for access to the water. Two 10 × 10 cm. wooden strongbacks were put over the hole. From one a wooden ladder was secured with a descending line hanging 50 m. into the water, and from the other a diving stage was suspended to just below the underside of the ice (4 m.). The stage was to be used for the divers to place cameras and make last minute adjustments before proceeding under the ice.

An oil stove was installed for warming the hut. Under normal conditions, this heater provided a comfortable 15°C and kept the surface of the water in the hole from refreezing, but when the wind came up the internal temperature dropped to about 0°C, necessitating the partial sealing of the sides of the hut to the sea ice with snow. A portable gasoline generator, delivering 2½ kw., furnished power for the underwater floodlights and interior lighting.

*Diving.*—A summary of dives is given in Table 1. Diving was begun on October 31 when, after several days of "white out" and winds of up to 70 knots, the wind velocity dropped to about 20 knots and the diving team was able to conduct a short test dive to check the operation of the demand regulators and the effectiveness of the wet suits.

Dressing in the exposure suits was done at the Biology Laboratory at McMurdo, about a mile and one-half from the hut. Transportation to the diving site was by a heated tracked vehicle. The suits provided protection against the air temperature when supplemented with a parka, hat and mukluks. The remainder of the diving equipment was put on in the hut just prior to entering the water. Under the cold conditions of October-November, and particularly when the hut was not sufficiently sealed against wind, it proved to be almost impossible to prevent the formation of new brash ice at the surface of the hole.



TEXT-FIG. 2. Diagram of diving hut and method of sub-ice operations. See text for full explanation.

This was cleared before each dive. Ice crystals were also continually formed on the undersurface of the ice early in the season and the entry and exit of divers freed these, which floated up into the ice-hole to thicknesses of up to about 1 m. This offered no particular problem except the impossibility of seeing up or down through the hole and partially obscuring the hole as well. A net was almost constantly in use by aides in clearing this brash ice. A method used by Biological Laboratory personnel involved hole warmers extended into the water to keep water temperatures in the ice-holes just above the freezing point.

Each dive was planned as to length, depth and purpose before entering the water. Descent was made by ladder and then to the diving stage just under the ice for rendezvous. Brash ice and crystals were cleared from around the bottom of the hole by hand by the divers upon rendezvous.

Orientation to the ice-hole was provided by the white nylon descending line, and the orange diving stage. Additional orientation was provided by a flashing Xenon beacon, attached at 10 m. depth on the descending line, which emitted a 250,000 candle power flash every 1 second. Sorties were restricted to 10 m. horizontally from the descending line. Additional distance would require a tending line.

After initial testing of diving equipment, dives were made for physiological purposes and to check visability, currents, floodlights and photographic equipment. Two 15-inch brass reflectors, each with a 1,000-watt bulb, were mounted on a four-foot wooden crossbar and trained to illuminate an area approximately ten feet away. The light array was buoyed with a cork float on a line about 2 m. long. By permitting the buoy to rest against the underside of the ice, the lights could be left unattended. Small styrofoam floats were strung on the heavy electric cable to compensate for its weight.

## COMMENTS ON EQUIPMENT AND OPERATIONS

*Wet Suit.*—One of the most critical items of polar diving operations is the exposure suit. Neushul (1961) has discussed the relative merits of wet and dry suits. The 6 mm. neoprene suit, worn in layers as described above, offers adequate protection, if there is no flooding. The biggest problem in this respect was water entry in the gloves, boots and down the neck of the outer jumper. The following modifications in the suit described are suggested: (1) the boots should be incorporated in the pants or have a long overlap in cuff and pants. It will be found a little difficult to get out of such boots but worth the effort for dry feet; (2) the three-fingered gloves should be very carefully fitted, for the slightest restriction in the fingers will impede circulation and cause numbness. The gauntlet part of the glove should be tapered and cut to reach just below the elbow to prevent leakage; (3) the undershirt should have a high neck with a detachable 3 mm. hood. The outer jumper should have an attached hood of 4.5-6 mm. material. This outer hood must be very carefully tailored to fit over the inner helmet for good seal against water entry. Neushul stated that no part of the face should be in direct contact with the water if diving was to be continued for extended periods. Peckham did not find this to be the case, nor did we, and we did not design the hood to completely cover the mouth with a slit or hole for the regulator mouthpiece as used by Neushul. That arrangement we thought might be overly cumbersome should the mouthpiece have to be removed and replaced, as happens at times. Bunt found any exposure to the forehead to be extremely uncomfortable and this was confirmed by us; (4) detachable flutter valves (non-return) may be fitted on the back of the outer helmet, the upper part of the jumper and at the top of each thigh to aid in the expulsion of trapped air upon diving, and provide a means for injecting warm water after surfacing and venting of the suit when undressing.

*Rewarming.*—Warm water and towels proved to be extremely effective in rewarming the diver. The face and hands were immediately doused and dried upon emergence from the water.

*Fins.*—Fins should be loosely fitted with heel "Y" straps to keep them firmly on the feet.

*Weight Belt.*—The weight belt must be secure, yet easily jettisoned if necessary. The buckle must be of such a size as to permit operation with heavy diving gloves. The large lever-type buckle that releases with one hand is the most desirable. On one occasion out of water, an attempt was made to release the weight belt without success. The buckle had frozen and the bulky gloves made its operation impossible.

*Face Mask.*—The glass should be tempered, as is usual for the best quality face masks. The skirts should be very pliable. The mask and hood should be fit within 1 cm. or less.

*Tank.*—Twin bottles are recommended for their increased operating time. Single bottles are more comfortable and have sufficient air for normal dives when the diver does not go over 20 m. However, when the diver depends upon one hole for exit he may find a 500 kg. seal or other obstruction in it when ready to surface. In such a case the diver might have to wait patiently until the animal has completed breathing. The twin bottles would allow longer endurance. Loss of orientation or rescue operations also demand longer potential diving time.

*Reserve.*—The ring on the end of the reserve pull rod ("J" valve type) should be at least 7 cm. in diameter to accommodate the gloved thumb. It is impossible to hook the gloved thumb through the rather small ring at the end of rods provided as standard equipment. This difficulty had been anticipated and a larger ring had been fashioned before diving.

*Regulator.*—Underwater, we found that breathing was normal and not noticeably different from any other dive in warmer waters. Ice formed on the high-pressure stage of the regulator without malfunction. While still rigged for diving and wet after ascent, both divers went outside the hut to expose the equipment to the −20°C air temperature. A regular rate of breathing was maintained on the apparatus to determine if the regulator would become blocked with ice. The block of ice on the back of the regulator increased in size but there was no resistance to breathing.

*Diving Ladder and Stage.*—An adequate means for entering and exiting the water is of great importance. Frequently, a diver returns to the ladder with numbed hands and feet, and it is difficult to get out of the water. A good method is the use of a fireman's type of ladder (Text-fig. 2 and Plate II). A diver can pull himself up by his forearms if the hands are numbed.

The stage is used as an accommodation for placing equipment. It should be in a basket shape so that it is not necessary to lash down anything placed on it.

*Light Rigging.*—Heavy equipment, such as the floodlights, must be as close as possible to neutral buoyancy. Buoyancy is a very difficult problem because it is constantly changing with the amount of cable that is paid out. Experience showed that a buoy, with considerable positive buoyancy, can be hard to handle. If lights are to be used some distance from the hole, the buoy should provide only a few pounds of positive support and should be on a short line 1 m. long at most. The equipment then can be released, if momentarily not needed, so that it will come to rest against the underside of the ice. However, buoying equipment with any lines can be of considerable disadvantage in maneuverability because buoying lines increase the possibility of entanglement. For instance, on one occasion some difficulty was experienced with the floodlights during a dive to take 16 mm. motion picture sequences. In order to position the buoy, it was necessary to pull up on the weight of the descending line. Several feet of cable had been paid out from above and hung in a bight below the divers. When Lavallee released the descending weight, it caught the cables and hauled him down. One of the lines became entangled in the supply hose of the regulator and pinched off the air. At this moment, a large bull Weddell Seal swam into the area and surfaced in the ice hole. It appeared for a moment that Lavallee would have to squeeze past the animal to get air on the surface. However, the hose came free, making this unnecessary.

*Orientation.*—Under the clear conditions of October-November, the white nylon descending line and diving stage could easily be seen from 10-15 m. and the Xenon light for much farther. The hole could not be seen horizontally from even 5 m. from just the ice, but could be seen from below at up to 25 m. In murky water or at greater distance, each diver must use a guide line.

*Buoyancy.*—Table 2 gives data on weights that were necessary to achieve neutral buoyancy. We define neutral buoyancy or inhalation, with slightly negative buoyancy after exhalation. Achievement of neutrality is one of the most frustrating problems inherent in almost all exposure suits. It can be a factor of considerable danger as well. For instance, the wet suit compresses with descent; it loses insulating capacity directly with loss in thickness and negative buoyancy increases. Thus, without a constant volume arrangement, the diver is neutral only for one specified depth—a depth which must be planned *previously* to each dive. A diver trim for 10 m. with 12 kg. weights, descending to 25 m., would be negative 8 kg. Few divers can swim with this much excess and, if the descending line were not immediately at hand, the alternatives would be to sink (and perhaps drown),

Table 2. Buoyancy Data on Divers Wearing Exposure Suits Described in Text. Weights Were Worn on a Belt About the Waist.

| | Lavallee | Ray |
|---|---|---|
| Height | 6 ft. 0 in. (182 cm.) | 5 ft. 11 in. (180 cm.) |
| Weight | 175 lb. (77 kg.) | 165 lb. (75 kg.) |
| Waist | 33 in. (86 cm.) | 32 in. (64 cm.) |
| Type | Mesomorphic | Mesomorphic |
| | Positive Buoyancy | |
| Surface | 35 lb. (16 kg.) | 32 lb. (14.5 kg.) |
| 10-30 m. | 26 lb. (12 kg.) | 25 lb. (11.5 kg.) |
| 25 m. | 10 lb. (4.5 kg.) | 10 lb. (4.5 kg.) |

or to drop weights, and/or to inflate a safety vest. In the latter case, a special problem occurs in sub-ice Antarctic diving. A vest would arrest descent but as the diver ascends and still cannot find the descending line, he will float up at accelerating speed to rise into the thick brash ice which is present. Finding a way back to the ice-hole against such positive buoyancy with a cumbersome inflated vest in the brash ice would be difficult or impossible. The use of a safety vest is not to be regarded as safe under ice. If weights are dropped, the suit itself provides more than enough buoyancy for ascent from depths of 50 m. or more.

Such buoyancy problems comprised the main reason for limiting all vertical movements to the descending line, grasping the line and testing buoyancy and only venturing from it horizontally after achieving neutrality. If a problem such as sudden vertigo were to hit a diver away from the line without neutrality, one possible result would be drowning should the second team member fail in recovery.

*Teamwork.*—A diving team is normally a pair, acting as one man. Under Antarctic conditions, we found it mandatory that the team be augmented by one or two surfaces aides. If two teams are to be used, these could be alternated to extend diving time in repetitive dives; the surface team would act as aides for the submerged pair. Aides are important because, dressed in thick suits and wearing heavy gear, the diver out of water or at the surface is clumsy in the extreme. Normal movements are further encumbered by fatigue and numbing due to cold. Surface aides serve to keep the ice-hole clean and to maintain warm water and supportive gear ready for immediate use.

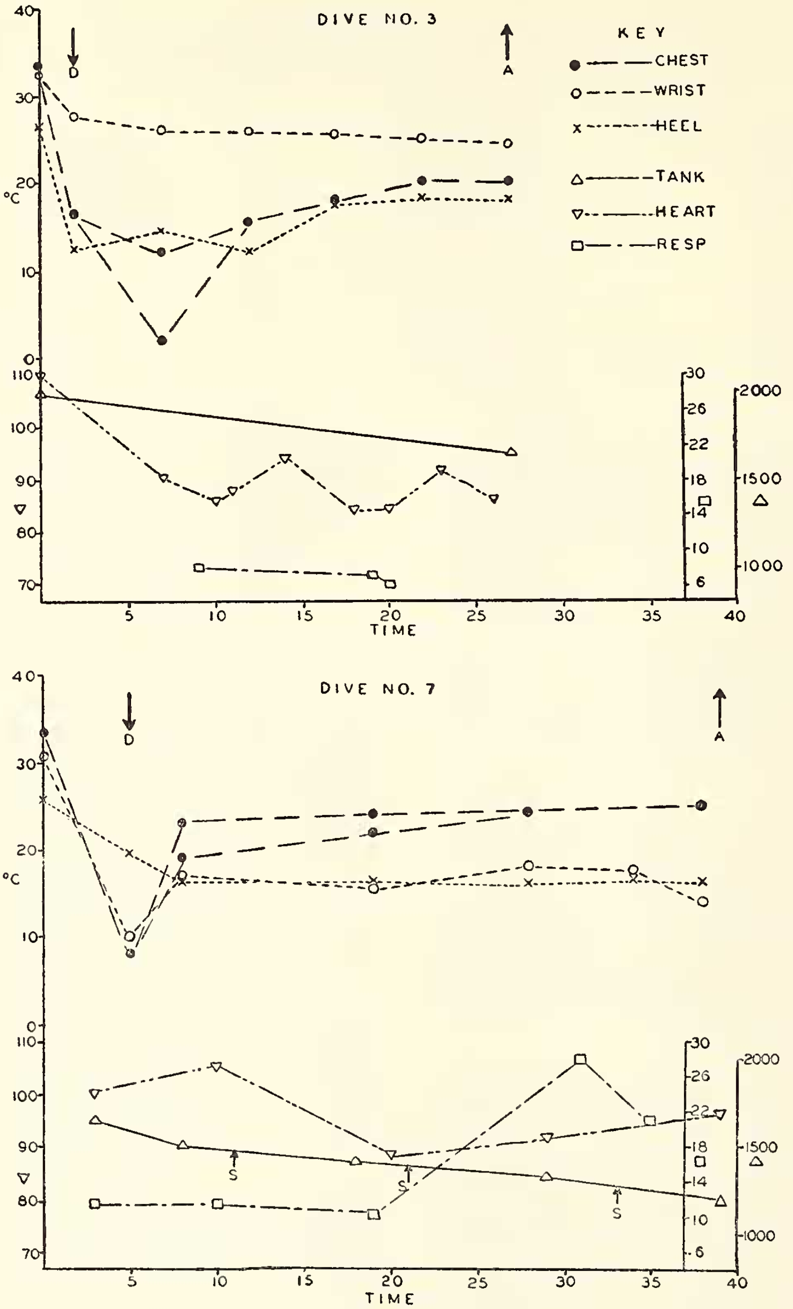
*Mobility.*—Dive number 8 (see Table 1) was made in an ice-hole a mile from the diving hut. We found no difficulty in dressing and loading as usual, moving the diving ladder with descending line and weight to the new location and diving. Mobile operations considerably farther from a diving base are perfectly feasible, as are field operations from a heated vehicle or helicopter.

*Diet.*—Caloric requirements (see "Physiology" below) are high during cold-water diving, at least 5,000 calories and possibly as much as 7,500 calories per day. If work is to be carried out far from a well-equipped base, food becomes a major item of logistics.

*Time.*—An entire dive, barring complications, approximated 2½ to 3 hours in time from dressing in the Laboratory to redressing there. Since the suits were excellent protection from ambient weather, considerably longer trips from base are perfectly feasible if adequate clothing and survival gear are also taken so that undressing could be done in the field. Neushul (1961) reports up to 6 hours' field operation dressed in a wet suit similar to the one we have described.

Two, or at the very most, three such dives might be attempted in a day, though it must be emphasized that each dive can entail considerable heavy work and even a two-dive day can be exhausting. Underwater diving time, as will be apparent under discussion on physiology, could perhaps be extended to hour periods provided that the diver remained active enough to generate sufficient heat to maintain the suit-skin temperature gradient over extended periods. Use of a larger hut than was available to us would save energy by eliminating the necessity of returning to the laboratory between dives.

*Data Recording.*—Both still and motion picture photography are advisable, though still black and white photography is simplest in the low light intensities encountered. Stroboscopic light is preferred because of the ease of operation without light bulbs and because of the speed of flash. For still photography we used the 35 mm. Calypso or Nikonos camera with 50-watt-second strobe designed by Harold Edgerton of The Massachusetts Institute of Technology. An excellent system of data-recording would involve

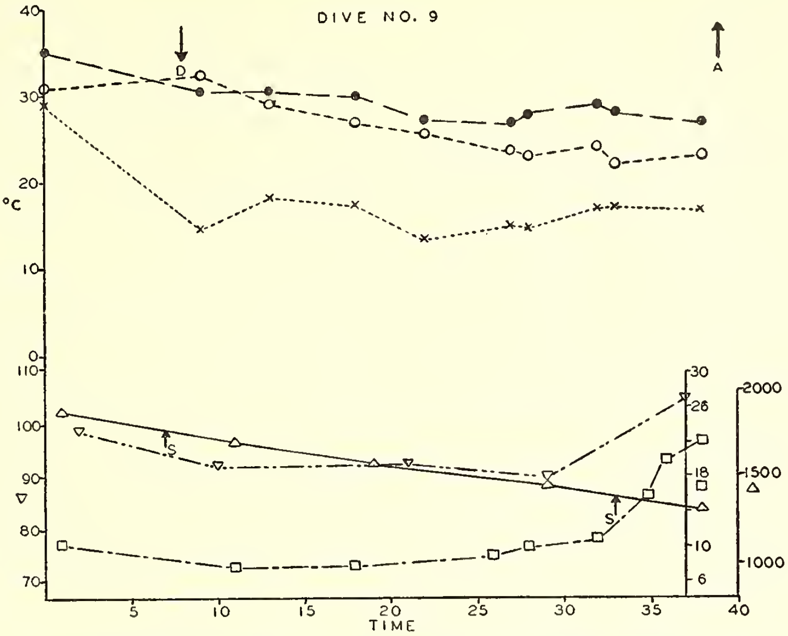


Text-fig. 3a **(Dive No. 3)** and 3b **(Dive No. 7).** See text for full explanation. Times of entry and exit from water are marked with arrows. S= time sample exhaled air taken.

an underwater communication and tape recording facility. Several such systems have been designed (Breslau, Zeigler & Owen, 1962) and are available, but we have not field-tested any of them.

## Physiology

Previous papers on the subject of polar diving have contributed to technology, but few physiological data have been gathered under field conditions. On dives 3, 7 and 9, Lavallee was the



Text-fig. 3c **(Dive No. 9)**. See text for full explanation. Times of entry and exit from water are marked with arrows. S = time sample exhaled air taken.

subject of certain tests designed to establish possible endurance limits. The test dives were conducted in the ice hole with the diver hanging motionless on the descending ladder and with the head just below the suface. Results are shown on Text-figs. 3, 4 & 5.

*Method and Equipment.*—Skin temperatures were recorded on the bare chest, the ankle-heel region and the wrist-palm region by means of thermistor leads from a YSI Tele-thermometer inserted under the wet suit. Electrocardiograms were obtained with a battery-operated Cambridge Trans-Scribe with leads inserted under the suit to the ankles and wrists. Both the telethermometer and EKG wires caused some flooding into the suit, as is shown by temperature drops after immersion (Text-fig. 3), but since the subject remained motionless, further flooding did not occur and the water soon warmed so that it is improbable that there were significant heat losses. For instance, little flooding occurred on dive 9 and submersion time was not extended. Respiration rates were observed directly by means of the intermittant bubble stream from the regulator. A polyethylene tube attached to the regulator exhaust funnelled respiratory exhaust gases to the surface where they were collected with a syringe for transfer to a Scholander 0.5 cc. analyzer (Scholander, 1947). Continuous tank pressures, directly proportional to $0_2$ utilization, were read directly by means of the pressure gauge attached to the regulator during diving.

Dive 3, the initial test, was purposely shorter than dives 7 and 9. The latter two dives were carried almost to the limit of the subject's endurance.

*The Subject's Observations.*—The precedure outlined was extremely uncomfortable for the diver after about 20 minutes of submersion.

Lavallee reported two periods of cold stress on each of the test dives and these are confirmed by the data. One was just after submergence when certain flooding occurred and limited amounts of cold water came into contact with the skin. The second occurred after 20 minutes and increased thereafter. During the last 10 minutes of each dive, the extremities became painful and/or numbed. The subject was aware of greatly increased respiratory rate and shivering during the terminal stages of each dive, especially numbers 7 and 9. His impression was that another 10 minutes in the water might have been impossible.

At terminus of dive 7, Lavallee reported that the "hands were dead due to lack of circulation," that "spasms and a sick feeling" were experienced, and that he had had "difficulty in breathing, particularly on exhalation. It was as if I had indigestion and I felt little pains or kinks at the sides of the throat near the clavicle." It is difficult to say what caused these symptons, but they appear to be assoicated with the increased respiratory rate observed.

During the mid-stages of dive 9, Lavallee voluntarily increased the rate of respiration and reported feeling warmer as a result, probably due to the increased muscular activity of respiration. This is not in contrast with the observations on dive 7, above, because during the initial minutes of a test dive the subject is in better control of respiration than at terminus when shivering and respiratory rate increase more or less involuntarily.

Upon emergence from each test dive, warming was rapid. The subject reported feeling "normal" within 5 to 10 minutes and expressed willingness to dive again.

It was not possible to test adequately such problems as susceptibility to vertigo, loss of orientation, nitrogen narcosis threshold, and low temperature torpidity and cramps as originally planned. However, some observations were made. During one dive to 25 m., Lavallee's suit flooded up under the jumper. After a very few minutes he became rather uncomfortable and suspected that duration under such circumstances would have been about 10 minutes, which agrees with both Neushul's and Fane's comments. No cramping occurred. On another dive to the same depth after a purposely increased respiration rate to about 60 per minute. Lavallee began to ascend and experienced vertigo-like dizziness which disappeared after a pause at 12 m. on the descending line. Ray has experienced vertigo at 25 m. in water of 4°C. We cannot identify the cause, but possibly it is due to a sudden flooding of one of the ear canals with cold water or loss of $CO_2$ with hyperventilation. Vertigo is especially dangerous at depth under ice, since orientation is lost.

On another occasion, Lavallee pulled the outer hood chin cup down and away from the face and ears. Contact with water proved painful, especially around the chin and temples. The mouth and cheeks more easily tolerated the cold and the jaw muscles did not cramp. Vertigo was not experienced.

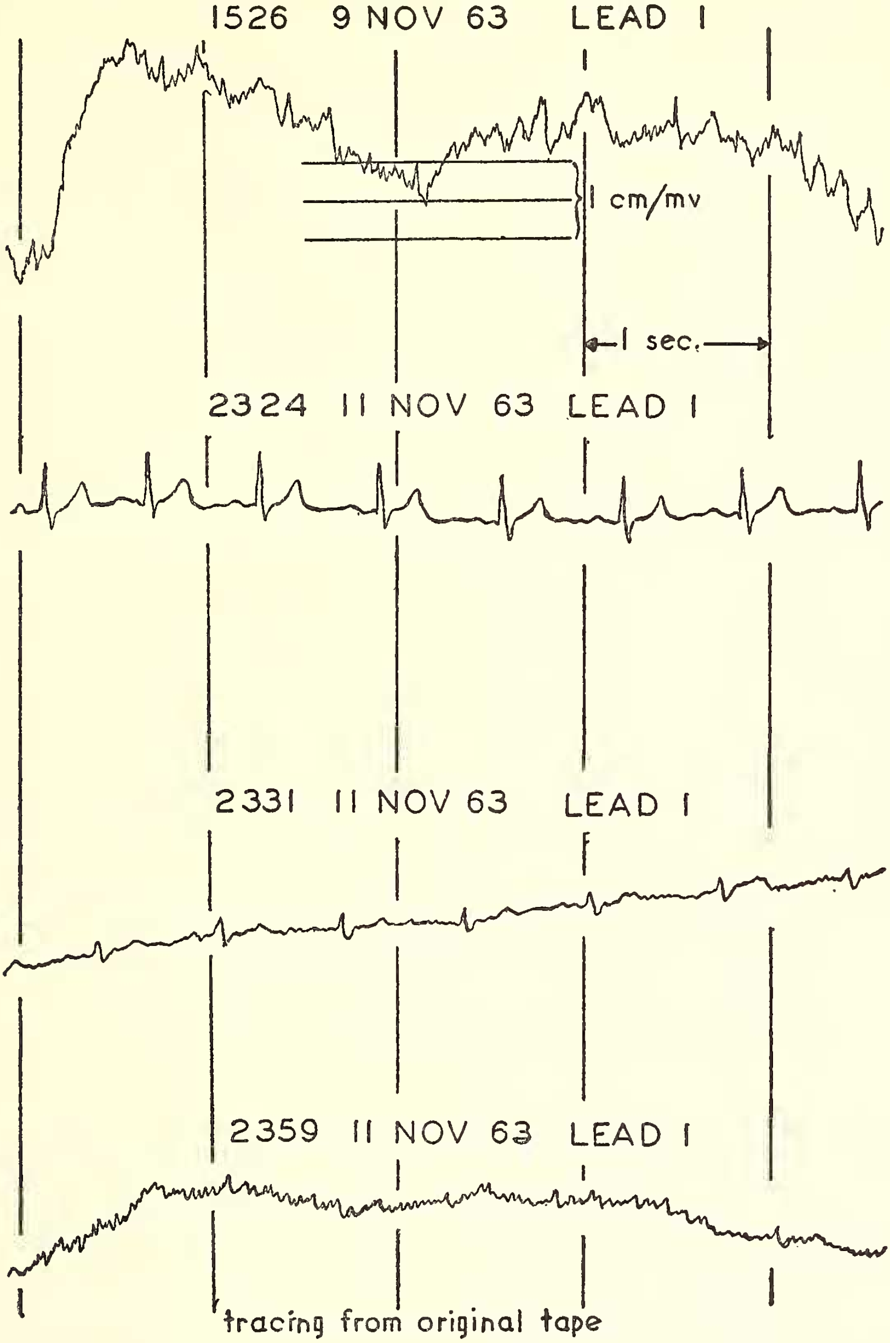
*Skin Temperatures.* — Temperatures of the wrist-palm, ankle-shin and chest are given in Text-fig. 3. In air of 24°C (about room temperature), Lavallee maintained normal resting temperatures while bare-chested, but wearing light pants, as follows: Chest 31°, ankle-shin 29°, wrist-palm 30°. Fully dressed in a wet suit just prior to entry on the test dives, these temperatures were 33-35°, 25-29° and 31-32° respectively. The elevated temperatures were due to activity and insulation of the wet suit. Immediately after immersion, depression in all these values was clearly but irregularly evidenced. The lowest temperatures recorded were 2°, 12° and 10° respectively. Thereafter, all temperatures rose as the water in the suit was heated by the body, then leveled off at about 20-30°, 14-18° and 18-26° and did not show terminal depression as might be expected. No temperatures were taken at the tips of the extremities and none internally.

*Heart Rate.*—Rates are shown in Text-fig. 3 and sample EKG's are given in Text-fig. 4. Due to shivering, and water interference, the EKG's could not be used for analysis of heart action, but rates are indicated. Lavallee's normal resting rate was measured at 72 and 80 on two occasions in the laboratory. No conclusive or consistent alterations of heart rate are indicated. Slowing from 100-110 to 85-95 after immersion was to be expected, since the work load was decreased. Several unexplained alterations in rates, perhaps due to alterations of breathing rate, are seen. Depression of rate or cardiac arrest, often associated with severe internal temperature depression, were not seen in any dive. Text-fig. 5 (a) shows the heavy shivering which is characteristic at terminus and is a good indication of involuntary metabolic adjustment being made in an effort to keep internal temperatures normal.

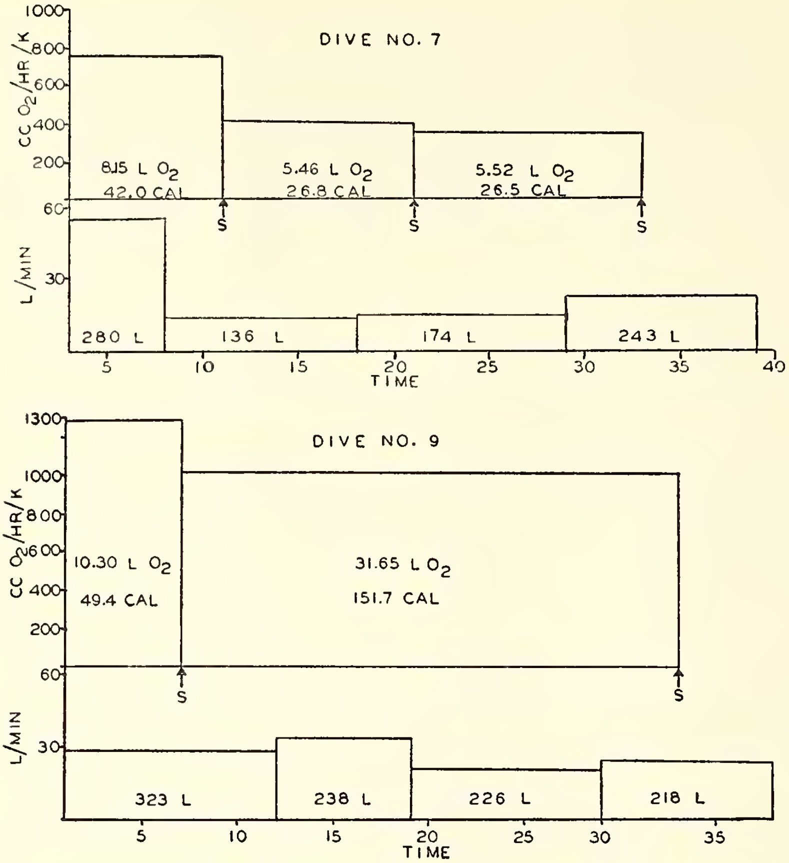
*Respiratory Rate.*—Certain unreliability must be attached to observed rates since these are partially under control of the subject. There is a tendency on the part of divers to unconsciously control the rate of respiration. Nevertheless, at termination, there is a strong increase in the rate of respiration, as shown on Text-fig. 3. This was associated with the diver's feeling cold and with shivering.

*Metabolic Rates.*—The regular fall in tank pressures on dives 7 and 9 is shown in Text-fig. 3. Details of metabolic analysis are given in Text-fig. 5. From tank pressure, the air volume consumed can be calculated and the results of dive 7 show what we believe is the more typical case of the two. Initial consumption was high, approaching 60 liters per minute. After adjustment to the water while remaining perfectly still on the diving ladder, the gas consumption fell as did the heart rate. At terminus, the rate picked up due to subject chilling and resulting increased respiration rate and shivering. Dive 9 did not show such dramatic variation, but both dives agree in the terminal stages in that the final consumption approached 25 liters per minute at the surface, which is 30% higher than our average in warmer waters.

Three gas samples were taken on dive 7 and two on dive 9. $O_2$ and $CO_2$ analyses differed for



TEXT-FIG. 4 **(A)**. Example of severe shivering, from an EKG taken 34 minutes after entry, Dive No. 7. Time is given by upper left number. **(B)**. EKG on surface before entry into water, Dive No. 9. **(C)**. EKG 2 minutes after descent, Dive No. 9. The impulse is not so strong, due to electrical interference of the water. **(D)**. EKG 30 minutes after descent, Dive No. 9. Shivering is evident.



Text-fig. 5a **(Dive No. 7)** and 5b **(Dive No. 9)**. Air and $O_2$ consumptions during Dives 7 and 9. Lower blocks indicate volume of air utilized during the test period indicated. Numbers within these blocks give volume in liters. Upper blocks represent volumes of $O_2$ utilized. Numbers within these blocks give volume $O_2$ in the test period indicated and its equivalent in terms of Calories of energy expended. S = time of exhaled air sample (see Text-fig. 3). See text for full explanation.

the two dives. From these data, R.Q. and oxygen consumption have been calculated. These data are more revealing than air consumption since $O_2$ utilization was not equal throughout. Gas consumption was initially high in both dives in this case, and in spite of increased respiratory rate the $O_2$ consumption did not rise at terminus, indicating that increased respiration alone cannot increase respiratory efficiency. In all samples but one, the R.Q. was near 0.8. Initially on dive 7, the R.Q. was 1.02. Caloric utilization has been calculated using 5.15 Cal. per liter $O_2$ at R.Q. = 1.0 and 4.8 Cal. per liter $O_2$ at R.Q. = 0.8. The total calories utilized in terms of $O_2$ consumption on dives 7 and 9 are 95.3 and 201.1 respectively. These are widely divergent values, but both agree in being extremely high for a man at "rest," which is the state approximated after the initial "work" stage of each dive. The lowest Cal./min. values on each dive were 2.21 and 5.7 respectively. The highest values, during the work stage before and just after entry; reached 5.25 and 8.25 respectively.

*Physiological Conclusions.* — Man possesses few adaptations for the conservation of heat. His only defenses against cold are shivering, voluntary muscular activity and whatever insulation he may be able to devise. Witwer (1958) states that in water of 0°C, naked man's survival time is less than 1 hour. Seals immersed in freezing water allow a gradient to occur in which the skin temperature falls to near zero whereas the muscles a few inches under the thick blubber are nearly 37°C, but in man the capacity for vasoconstriction is poorly developed. This means that the heat produced internally is dissipated rapidly at the surface.

The internal temperature in most warm-blooded animals, including man, cannot be allowed to fall much below 37°C. Fane (1959) states that: "The average body temperature of swimmers returning to the ship was 34°C." However, he does not say how these temperatures were recorded and we doubt that this drop is representative of true internal temperature. The U. S. Navy Diving Manual (1963) states that: "A man can live and function effectively only if the temperature in his body remains close to normal: 98.6°F. (37°C)." We did not record internal temperatures, but presume these did not drop significantly during dives, a conclusion reinforced by the statements of Scholander, et.al., (1950a) that the least variable factor in homiothermy is body temperature, which is regulated to within a degree in most mammals, and of Spector (1956) that the body temperature of a naked man immersed to the neck in water of 6°C for 32-49 minutes dropped only to 36° from 37.5°C.

It would now be worthwhile to summarize pertinent data on the physiology of man at low temperatures and under basal conditions. The subject of hypothermia has been reviewed by The New York Academy of Sciences (1959). Excellent reviews of the problems involved in heat regulation and cold adaptation among animals are found in Scholander, et.al. (1950a & 1950b). It is well to point out that critical temperature (below which metabolic activity must be increased to maintain internal temperature) is directly related to surface area, metabolic rate and insulation and that these must be adjusted so that a balance is achieved between them and the temperature gradient between ambient and skin. This statement is basic to thermoregulation.

The critical temperatures for naked man are 26-27°C in air (Erikson, et.al., 1956) and 32-36°C in water (Fletcher, 1964). Lightly clothed man's critical temperature is about 14°C (Erikson, et.al., 1956). His energy requirement is in the vicinity of 3,000-3,200 Cal. per day for men of 25-45 years of age while "engaged in moderate physical activity" (Heinz Nutritional Data, 1958) or between 1.19 and 1.8 Cal./min. for supine or sitting man (Spector, 1956). Data differ somewhat on normal body skin temperatures maintained, but in general man maintains 30-34°C in room temperature air. The U. S. Navy Diving Manual (1963) states that the skin begins to feel cool when its temperature drops to 31, and cold at 30, when shivering may occur. These are probably body and not extremity temperatures, which would be lower. At a skin temperature of 15°C, the hands feel intense pain.

With these general data in mind the skin temperatures recorded on test dives become meaningful. It is obvious that motionless man cannot maintain normally high skin temperatures while wearing a neoprene exposure suit of 6 mm. thickness on arms and legs, 15 mm. (for three overlapping layers) on the torso, and 9 mm. (for two overlapping layers) on the head. This is to say that heat loss is not totally impeded, only slowed, in these thicknesses over a gradient of −1.9° for water to the necessary 30° for the skin. Nor should the exposure suit be thick enough to maintain such a gradient lest during diving activity the necessary dissipation of body heat be prevented unduly. Heat is dissipated from the surface to water totally by conduction, which is not the normal human method and therefore a careful balance must be achieved between temperature gradient, activity and suit thickness. A consideration of suit bulk, changing activity rates, the high conductivity of water and the relatively huge 30°C gradient will show that, at the present state of technology, man cannot hope to achieve thermal neutrality in polar waters, but is limited severely in exposure time, which we have shown to be in the vicinity of 30 minutes motionless at the surface, and estimate to be perhaps twice that long with moderate activity. These times are reinforced by similar statements of Neushul (1961), Fane (1959) and the U. S. Navy Diving Manual (1963).

Erikson, et.al. (1956) have said: "A warm-blooded animal usually first compensates for a falling environmental temperature by gradually increasing the insulation while the metabolism remains at resting level. At the critical temperature, insulation reaches its maximum and from there on heat balance is obtained by increasing heat production. This increase has been found to be rather closely proportional to the body-to-air temperature gradient, such as would be expected from Newton's Law of Cooling." As stated above, the partially inadequate insulation of the suit already places man in polar waters well below his critical temperature. Activity is the only heat-producing mechanism left and it is obvious that this has physiological limits. We have shown that heat production in terms of $O_2$ consumption is between 2.21 and 8.25 Cal./min. from the "resting" to "work" stages of a normal Antarctic sub-ice dive, which is from about twice that of a man, supine, at rest in air to that of a man walking at a fair pace up stairs (Spector, 1956). There was little terminal increase in metabolic rate on either of the test dives in which

$O_2$ consumption was measured, probably because we did not carry any test dive to this fairly extreme point. Shivering and the muscular activity of increased respiratory rate were the responses observed. When these occur, the diver should immediately ascend and emerge, as is stated by other papers on this subject, for what might be called "escape time" before severe cold stress sets in is short in polar waters, at times amounting to minutes only. However, barring the occurrence of cold stress, rewarming time is also short. Therefore we believe that repeated short dives are psysiologically more feasible than longer dives in which chilling is severe.

Two other methods of increasing diving time might also be mentioned. One is the consumption immediately before submergence of sugared water for the immediate caloric heat and glucose supply it gives. Another is a technological consideration. The polar diver breathes air at ambient temperature, which exposes his lungs and increases heat loss. Warming and insulation of diving tanks so that the diver continually breathes warm air might be of some aid in reducing heat loss, but the specific heat of air is small.

## THE SUB-ICE ENVIRONMENT

Plates II and III show some features of the sub-ice environment but give little idea of the extreme clarity and good visibility of the waters at McMurdo Sound during October-November. The ice shown is a single season's accumulation of about 2.0-2.5 m. with a distinct ice crystal layer of up to 1.0 m. thickness on the under surface. From our experience plus valuable personal communication with Dr. Wohlschlag, Dr. Bunt and Mr. Verne Peckham, a picture emerges of water clarity as follows. At the winter's end, in September-October, the water and ice are more or less free of plankton and visibility is extremely good. It would be difficult to estimate the distance one could see, but on one occasion we had the opportunity to send a 30 m. line out horizontally from the diving hole and a Weddell Seal approximately 15 m. beyond the end of the line was clearly distinguishable. Dr. Wohlschlag (pers. comm.) reports photographing starfish and a fish trap clearly from the surface in 25 m. water depth. These distances approach the possible limits of clarity for water. During this "spring" period, various species of brown diatoms concentrate and "bloom" within the ice crystal layer. The diatoms do not interfere with clarity but do curtain out the available natural daylight so as to permit an estimated less than 1% penetration by late November and into December. Bunt (1964a and b) recorded 0.05-0.08% of surface illumination immediately below ice when the diatoms were at their peak. Concurrently, the water has been almost imperceptibly warming from −1.9° to about −1.7°C and this appears to have two effects. First, the under-ice crystal layer quite suddenly disappears, causing the diatoms to mix with the water. Second, the chrysophycean globular alga, *Phaeocystis*, is carried in by freshly introduced waters. Both of these factors serve to cloud the waters so that visibility may fall to 3 m. or less, but since the diatom curtain on the underside of the ice has largely disappeared, available light increases. Bunt (*op. cit.*) reported a light rise to 1.5% of available with the disappearance of the ice crystal layer, but states that it is difficult to separate light loss due to ice, diatoms and *Phaeocystis.*

When the ice goes out in mid to late summer, available light increases further and so does visibility. As fall and winter approach, available light decreases due to the declining position of the sun and the reduced photoperiod, but clarity increases further. Winter is once again dark but clear, which brings the season full cycle once again. There is a great deal of variation in every factor of this generalized story, but for diving practice one must separate light intensity and water clarity. Rarely does one have good conditions of both beneath ice in McMurdo Sound, at least not for photographic practice with any but fast black and white film. However, the naked eye is fully capable of adjusting to available light in under-ice surface waters ( to 25 m. depth or a little more).

One peculiarity of Antarctic waters is shown in Plate III, Fig. 5. When water temperatures are still −1.9°C, the water contains crystals, some quite large, of ice which float freely. These are particularly noticeable in the beam of floodlighting equipment and presumably disappear when the water warms slightly in the summer.

## MARINE LIFE

During the period in which we dived, McMurdo Sound was completely covered by heavy, solid sea ice and very little marine life was encountered. No bottom dives were made since the water under the diving hut was more than 50 fathoms deep. Weddell Seals were sighted on two occasions. The first time, a single adult male swam up into the ice hole while a diver was in the hole preparing for submergence. The seal ventilated there for 2-3 minutes (estimated) and backed out of the hole and departed. Two other divers were under the hole preparing for ascent when this occurred. The seal swam off about 50 m. just under the ice, turned around and returned. The divers continued their ascent and the seal swam to the last diver (Ray), took his left swim fin in its mouth, and rose into the ice hole with him and ventilated again for about two minutes. On another occasion, a seal swam to about 40 m., but appeared to be frightened by the floodlight array, the flashing Xenon light, or the divers, and did not venture closer. On no occasion was aggression evidenced.

Before diving in Antarctica, some consideration had been given to Leopard Seals, *Hydrurga leptonyx*, and Killer Whales, *Orcinus orca*, the most predatory of Antarctic animals. Neither was sighted. It was planned to monitor underwater sounds for the characteristic whoops of the Killer Whale as a safety measure, but since the nearest open water was several miles distant (about 20), this was not done.

No fishes were sighted in surface water, though species of *Trematomus* were being caught nearby by Biological Laboratory personnel. We looked among the ice crystal layer and suspect that fish might hide there, but could sight nothing. On one occasion a very large jellyfish was sighted from near the diving stage by Lavallee at a depth of about 25 m. The animal looked to be about 0.6 m. across the bell and was translucent blue-gray in color with long central tentacles, a dense peripheral array of short tentacles and was marked with radiating lines, about 6-8 in number.

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## EXPLANATION OF THE PLATES

### Plate I

Fig. 1. Diving hut on location on the sea ice of McMurdo Sound.

Fig. 2. Cutting through sea ice with chain saw.

### Plate II

Fig. 3. Extracting sample of exhaled air from a diver just under the water surface. Polyethylene tubing is attached to the regulator exhaust. Note diving ladder construction.

Fig. 4. Looking up along the descending line to the diving stage and ice-hole.

### Plate III

Fig. 5. Diver with light array of two 1,000-watt underwater floodlights, showing buoying and descending lines. Note reflections from ice crystals suspended in the water.

Fig. 6. Underside of the sea ice showing ice crystal layer. Darker areas are shadows and some diatom growth. Note close fit of mask around mouth and mask to minimize water-skin contact.